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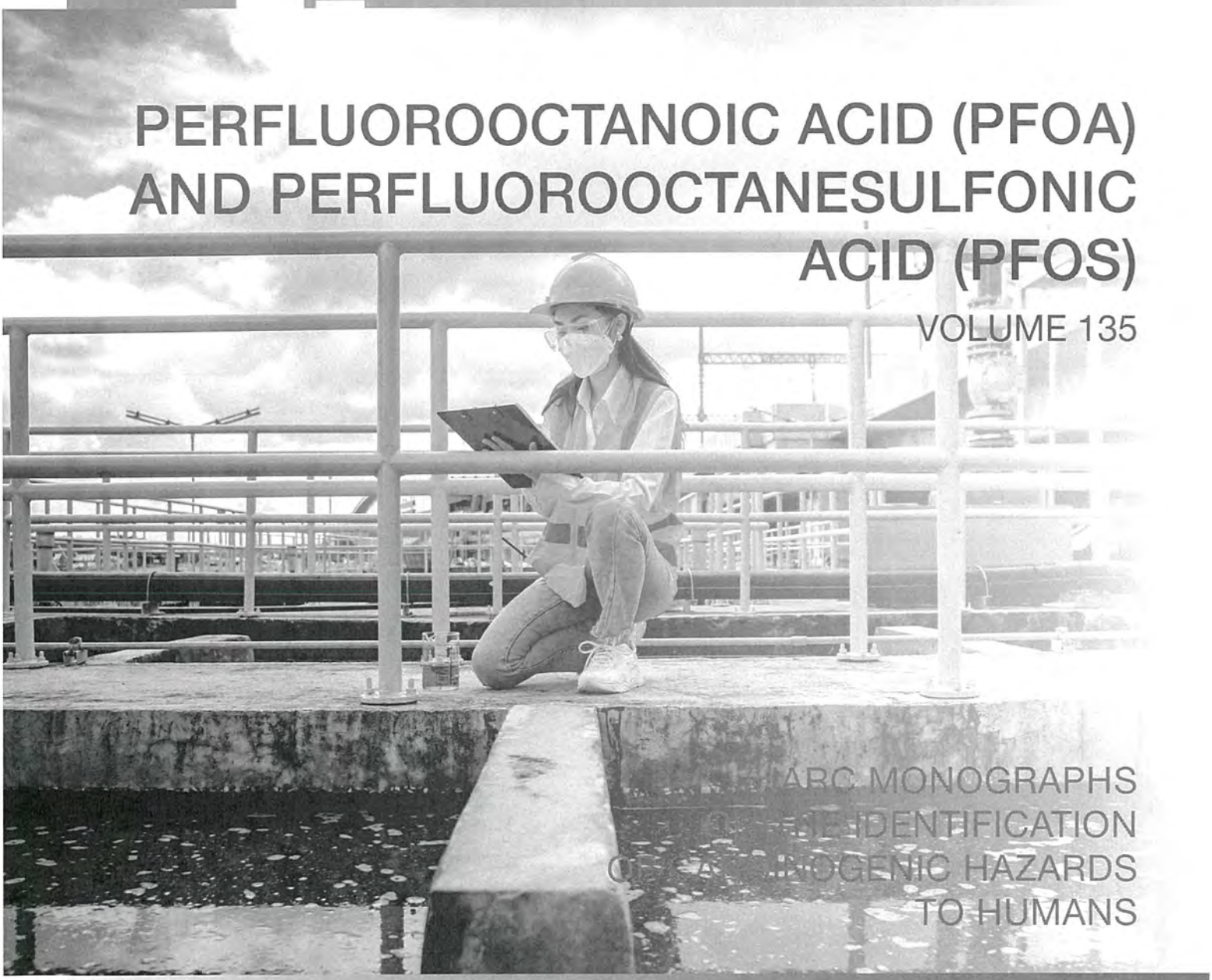

PERFLUOROOCTANOIC ACID (PFOA) AND PERFLUOROOCTANESULFONIC ACID (PFOS)

VOLUME 135

IARC MONOGRAPHS
ON THE IDENTIFICATION
OF CARCINOGENIC HAZARDS
TO HUMANS

International Agency for Research on Cancer
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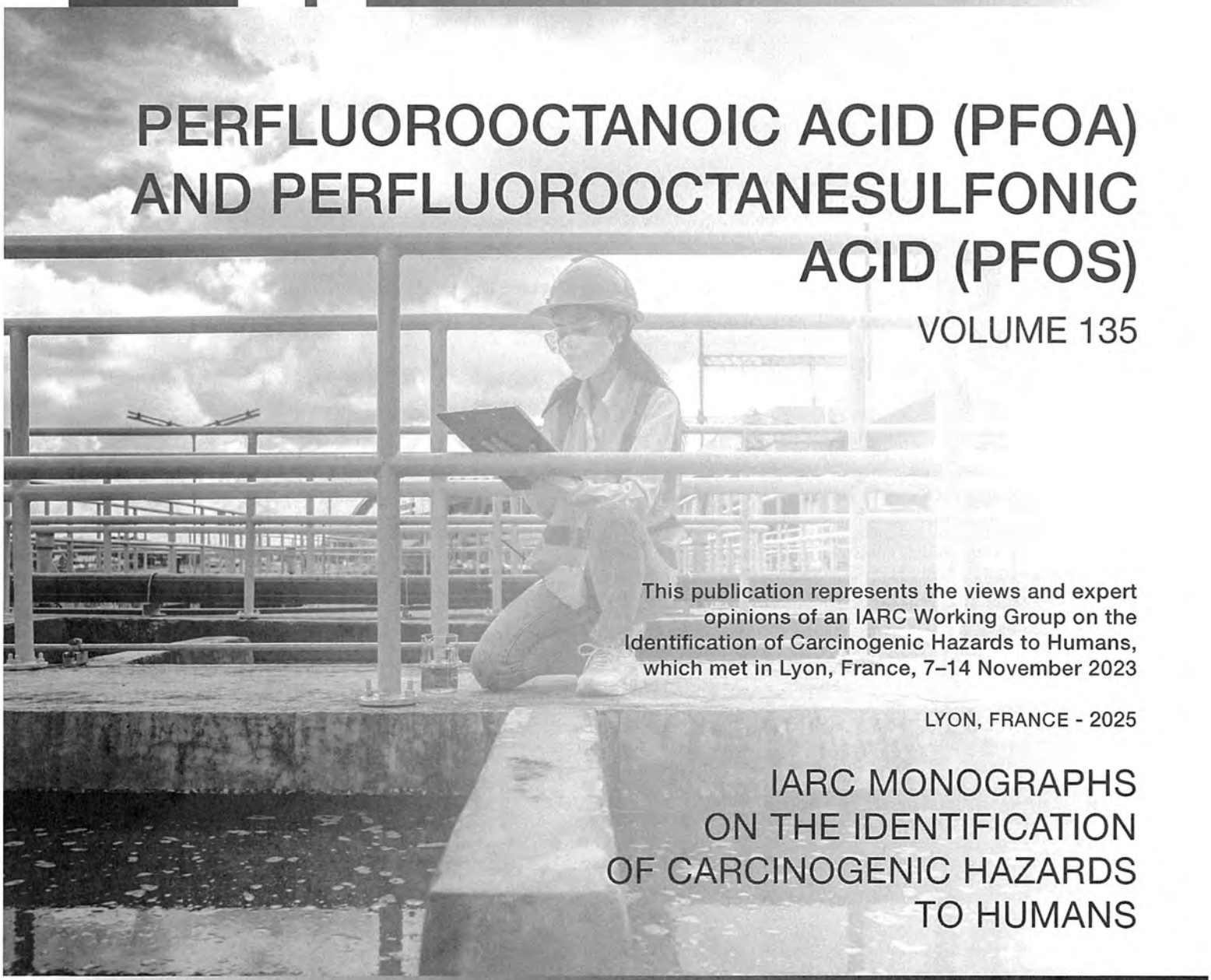

PERFLUOROOCTANOIC ACID (PFOA) AND PERFLUOROOCTANESULFONIC ACID (PFOS)

VOLUME 135

This publication represents the views and expert opinions of an IARC Working Group on the Identification of Carcinogenic Hazards to Humans, which met in Lyon, France, 7–14 November 2023

LYON, FRANCE - 2025

IARC MONOGRAPHS ON THE IDENTIFICATION OF CARCINOGENIC HAZARDS TO HUMANS

International Agency for Research on Cancer
World Health Organization

IARC MONOGRAPHS

In 1969, the International Agency for Research on Cancer (IARC) initiated a programme on the evaluation of the carcinogenic hazard of chemicals to humans, involving the production of critically evaluated monographs on individual chemicals. The programme was subsequently expanded to include evaluations of carcinogenic hazards associated with exposures to complex mixtures, lifestyle factors and biological and physical agents, as well as those in specific occupations. The objective of the programme is to elaborate and publish in the form of monographs critical reviews of data on carcinogenicity for agents to which humans are known to be exposed and on specific exposure situations; to evaluate these data in terms of cancer hazard to humans with the help of international working groups of experts in carcinogenesis and related fields; and to identify gaps in evidence. The lists of IARC evaluations are regularly updated and are available on the internet at https://monographs.iarc.who.int/.

This programme has been supported since 1982 by Cooperative Agreement U01 CA33193 with the United States National Cancer Institute, Department of Health and Human Services. Additional support has been provided since 1986 by the European Commission Directorate-General for Employment, Social Affairs, and Inclusion, initially by the Unit of Health, Safety and Hygiene at Work, and since 2014 by the European Union Programme for Employment and Social Innovation "EaSI" (for further information please consult: https://ec.europa.eu/social/easi). Support has also been provided since 1992 by the United States National Institute of Environmental Health Sciences, Department of Health and Human Services. The contents of this volume are solely the responsibility of the Working Group and do not necessarily represent the official views of the United States National Cancer Institute, the United States National Institute of Environmental Health Sciences, the United States Department of Health and Human Services, or the European Commission.

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About the cover: Worker at a wastewater treatment plant. PFOA and PFOS are ubiquitous in the environment and may contaminate drinking-water.

Source: © APchanel/Adobe Stock

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NOTE TO THE READER

The evaluations of carcinogenic hazard in the *IARC Monographs on the Identification of Carcinogenic Hazards to Humans* series are made by international working groups of independent scientists. The *IARC Monographs* classifications do not indicate the level of risk associated with a given level or circumstance of exposure. The *IARC Monographs* do not make recommendations for regulation or legislation.

Anyone who is aware of published data that may alter the evaluation of the carcinogenic hazard of an agent to humans is encouraged to make this information available to the *IARC Monographs* programme, International Agency for Research on Cancer, 25 avenue Tony Garnier, CS 90627, 69366 Lyon Cedex 07, or via email at imo@iarc.who.int, in order that the agent may be considered for re-evaluation by a future Working Group.

Although every effort is made to prepare the monographs as accurately as possible, mistakes may occur. Readers are requested to communicate any errors to the *IARC Monographs* programme. Corrigenda are published online on the relevant webpage for the volume concerned (IARC Publications: https://publications.iarc.who.int/).

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[3] Dr Fletcher reported providing expert opinion for plaintiffs in cases of exposure to PFOA in drinking-water in Italy and in the USA, and for the Government of Australia in defending against a class action lawsuit on behalf of communities seeking damages for drinking-water contaminated from use of aqueous film-forming foam (AFFF) on military airfields, and for the Government of Jersey in his capacity of member of the PFAS Scientific Advisory Panel.

[4] Each Observer agreed to respect the Guidelines for Observers at *IARC Monographs* meetings. Observers did not serve as Working Group members, draft any part of a monograph, or participate in the evaluations. They also agreed not to contact participants before the meeting, not to lobby them at any time, not to send them written materials, and not to offer them meals or other favours. IARC asked and reminded Working Group members to report any contact or attempt to influence that they may have encountered, either before or during the meeting.

[5] Dr Whu reported receiving support for travel from the International Association of Firefighters.

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6. EVALUATION AND RATIONALE

6.1 Cancer in humans

There is *limited evidence* in humans for the carcinogenicity of perfluorooctanoic acid (PFOA). Positive associations have been observed between PFOA and renal cell carcinoma and cancer of the testis.

There is *inadequate evidence* in humans regarding the carcinogenicity of perfluorooctanesulfonic acid (PFOS).

6.2 Cancer in experimental animals

There is *sufficient evidence* in experimental animals for the carcinogenicity of PFOA.

There is *limited evidence* in experimental animals for the carcinogenicity of PFOS.

6.3 Mechanistic evidence

There is *strong evidence* that PFOA exhibits multiple key characteristics of carcinogens in exposed humans, in human primary cells, and in experimental systems.

There is *strong evidence* that PFOS exhibits multiple key characteristics of carcinogens in exposed humans, in human primary cells, and in experimental systems.

6.4 Overall evaluation

PFOA is *carcinogenic to humans* (Group 1).

PFOS is *possibly carcinogenic to humans* (Group 2B).

6.5 Rationale

6.5.1 PFOA

The Group 1 evaluation for PFOA is based on the combination of *sufficient evidence* for cancer in experimental animals and *strong* mechanistic evidence of key characteristics of carcinogens in exposed humans. The evidence for cancer in experimental animals was *sufficient* because exposure to PFOA caused an increase in the incidence of an appropriate combination of benign and malignant neoplasms in both sexes of a single species (rat) in one study that complied with GLP. The mechanistic evidence was *strong* in exposed humans because PFOA induces epigenetic alterations and is immunosuppressive. In exposed humans, PFOA induces epigenetic alterations in the form of gene-specific methylation and cancer-related miRNAs. These effects are supported by evidence of epigenetic alterations in multiple experimental systems. In exposed humans, PFOA is immunosuppressive, increasing risk of infectious disease and decreasing vaccine response to diverse antigens. These effects are supported by evidence

of immunosuppression in human primary cells and experimental systems. In addition, in human primary cells and experimental systems, PFOA induces oxidative stress and modulates receptor-mediated effects. Additionally, in experimental systems, PFOA alters cell proliferation, cell death, or nutrient supply.

Also, for PFOA, the evidence for cancer in humans was found to be *limited* for renal cell carcinoma and cancer of the testis. Despite the increase in the number of available human cancer studies since the previous evaluation by the *IARC Monographs*, the results were somewhat inconsistent across the studies. For renal cell carcinoma, positive findings were observed in three studies conducted in partly overlapping occupationally and environmentally exposed populations and in a fourth population with background exposure. However, positive findings were not observed overall in two other background-exposed populations. For testicular cancer, there were two studies with positive findings: one cohort study and a second ecological study that had limitations. For other cancer types, there were only sporadic positive findings in the informative studies (e.g. breast), and for all these other cancer types, the evidence was *inadequate*.

6.5.2 PFOS

The Group 2B evaluation for PFOS is based on *strong* mechanistic evidence. There is *strong* evidence that PFOS exhibits multiple key characteristics of carcinogens in exposed humans, human primary cells, and experimental systems. There is strong evidence that PFOS in exposed humans induces epigenetic alterations in the form of gene-specific methylation and cancer-related miRNAs. These effects are supported by evidence of epigenetic alterations in multiple experimental systems. In exposed humans, PFOS is immunosuppressive, increasing risk of infectious disease and decreasing vaccine response to diverse antigens. These effects are supported by evidence of immunosuppression in human primary cells and experimental systems. In human primary cells and experimental systems, PFOS modulates receptor-mediated effects and induces oxidative stress. Additionally, in experimental systems, PFOS alters cell proliferation, cell death, or nutrient supply.

In addition, the evidence for cancer in experimental animals was *limited*. Exposure to PFOS caused an increase in the incidence of an appropriate combination of benign and malignant neoplasms in one sex (female) of a single species (rat) in a study that complied with GLP. The evidence regarding cancer in humans was found to be *inadequate*, because among the relatively few available studies, positive findings were seen only sporadically and inconsistently for a few cancer sites (i.e. breast, testis, and thyroid).

LIST OF ABBREVIATIONS

2-AAF	2-acetylaminofluorene
ACGIH	American Conference of Governmental Industrial Hygienists
ACOX	acyl-coenzyme A oxidase
ACS	American Cancer Society
ADME	absorption, distribution, metabolism, or excretion
AFB_1	aflatoxin B_1
AFFF	aqueous film-forming foam
AHR	aryl hydrocarbon receptor
AOR	adjusted odds ratios
APFO	ammonium perfluorooctanoate
AR	androgen receptor
ARE	antioxidant responsive element
ASTM	American Society for Testing and Materials
ATBC	Alpha-Tocopherol, Beta-Carotene Cancer Prevention
ATP	adenosine triphosphate
ATSDR	Agency for Toxic Substances and Disease Registry
AUC	area under the curve
BMI	body mass index
BrdU	bromodeoxyuridine
bw	body weight
cAMP	cyclic adenosine monophosphate
CAR	constitutive androstane receptor
CAT	catalase
CBD	cannabidiol
CEPA	Canadian Environmental Protection Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CGA	chlorogenic acid
CHDS	Child Health and Development Studies
CHO	Chinese hamster ovary
CI	confidence interval
CIOB	Chemicals in Our Bodies
CNBCSP	Chinese National Breast Cancer Screening Program
CoA	coenzyme A
ConA	concanavalin A

CONTAM	European Food Safety Authority Panel on Contaminants in the Food Chain
CpG	5′-C-phosphate-G-3′-dinucleotide
CPS	Cancer Prevention Study
CRP	C-reactive protein
CS	collagen sandwich
CTS	California Teachers Study
CV	coefficient of variation
CYP	cytochrome P450
DCF	2′,7′-dichlorofluorescein
DCF-DA	2′,7′-dichlorofluorescein diacetate
DCFH-DA	2′,7′-dichlorodihydrofluorescein diacetate
DEN	diethylnitrosamine
DFTJ	Dongfeng-Tongji
dG	2′-deoxyguanosine
DHEA	dehydroepiandrosterone
diPAP	polyfluoroalkyl phosophate diester
DMBA	7,12-dimethylbenz[*a*]anthracene
DMR	differentially methylated region
DMSO	dimethyl sulfoxide
DNMT	DNA methyltransferase
DoD	Department of Defense
DoDSR	Department of Defense Serum Repository
DOX	doxycycline
DTH	delayed-type hypersensitivity
EC	European Commission
EC_{50}	half-maximal effective concentration
ECA	Environment and Childhood Asthma
ECCC	Environment and Climate Change Canada
ECF	electrochemical fluorination
ECHA	European Chemicals Agency
EFSA	European Food Safety Authority
eGFR	estimated glomerular filtration rate
ELISA	enzyme-linked immunosorbent assay
EPCRA	Emergency Planning and Community Right-to-Know Act
ER	estrogen receptor
ERS	endoplasmic reticulum stress
ESI	electrospray ionization
N-EtFOSAA	*N*-ethyl-perfluorooctane sulfonamido acetic acid
EU	European Union
EWAS	epigenome-wide association analysis study
FDR	false discovery rate
FMC	Finnish Maternity Cohort
Fpg	formamidopyrimidine-DNA glycosylase
FSANZ	Food Standards Australia New Zealand
FT3	free triiodothyronine
FT4	free thyroxine
FTOH	fluorotelomer alcohol
GBCA	Genetic and Biomarkers study for Childhood Asthma
GC	gas chromatography
GDP	guanosine diphosphate

GF	glomerular function
GFR	glomerular filtration rate
GGT	gamma-glutamyl transferase
GJIC	gap junctional intercellular communication
GLP	Good Laboratory Practice
GM	geometric mean
GM-CSF	granulocyte-macrophage colony-stimulating factor
GPx	glutathione peroxidase
GRULAC	Group of Latin America and the Caribbean
GSH	glutathione
GSPE	grape seed proanthocyanidin extract
GSR	glutathione reductase
GSSG	oxidized glutathione
GST	glutathione *S*-transferase
γH2AX	phosphorylated H2A histone family member X
HBM	Human Biomonitoring
HBM4EU	Human Biomonitoring for Europe
HCC	hepatocellular carcinoma
HETE	hydroxyeicosatetraenoic acid
HFD	high-fat diet
HGF	hepatocyte growth factor
Hib	*Haemophilus influenza* type b
HMC	human mast cell
HMVEC	human microvascular endothelial cells
HO-1	haem oxygenase 1
HOME	Health Outcomes and Measures of the Environment
HPLC	high-performance liquid chromatography
HR	hazard ratio
HUVEC	human umbilical vein endothelial cell
IARC	International Agency for Research on Cancer
IC_{50}	half-maximal inhibitory concentration
ICC	intraclass correlation coefficient
IFN-γ	interferon gamma
Ig	immunoglobulin
IKIDS	Illinois Kids Development Study
IL	interleukin
INHAND	International Harmonization of Nomenclature and Diagnostic Criteria for Lesions in Rats and Mice
iNOS	inducible nitric oxide synthase
INSR	insulin receptor
i.p.	intraperitoneal
IQR	interquartile range
IRR	incidence rate ratio
IsoF	isofuran
IsoP	isoprostane
ITRC	Interstate Technology and Regulatory Council
i.v.	intravenous
JEM	job-exposure matrix
KC	key characteristic of carcinogens
KEEP	Korean Elderly Environmental Panel
KLH	keyhole limpet haemocyanin

LC_{50}	median lethal concentration
LC-MS/MS	liquid chromatography-tandem mass spectrometry
L-FABP	liver fatty acid-binding protein
LH	luteinizing hormone
LINE-1	long interspersed nuclear element 1
LLE	liquid–liquid extraction
LMIC	low- or middle-income country
LOD	limit of detection
LOQ	limit of quantification
LOX	lipoxygenase
LPS	lipopolysaccharide
LRTI	lower respiratory tract infection
LTL	leukocyte telomere length
LWBC	Laizhou Wan (Bay) birth cohort
MCP-1	monocyte chemoattractant protein
MDA	malondialdehyde
MDL	method detection limit
MEC	Multiethnic Cohort
MHC	major histocompatibility complex
miRNA	microRNA
mRNA	messenger RNA
MLQ	method limit of quantification
MNNG	*N*-methyl-*N*′-nitro-*N*-nitrosoguanidine
MRL	minimum reporting level
MRP	multidrug resistance protein
MS	mass spectrometry
MS/MS	tandem mass spectrometry
MTT	3-[4,5-dimethylthiazol-2-yl]-2,5 diphenyl tetrazolium bromide
NAC	*N*-acetylcysteine
NADPH	nicotinamide adenine dinucleotide phosphate
NAFLD	non-alcoholic fatty liver disease
NAR	naringin; 4′,5,7-trihydroxyflavonone-7-rhamnoglucoside
NASEM	National Academies of Sciences, Engineering, and Medicine
NDAA	National Defense Authorization Act
NDI	National Death Index
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NeuroP	neuroprostane
NGF	nerve growth factor
NHANES	National Health and Nutrition Examination Survey
NHL	non-Hodgkin lymphoma
NHMRC	National Health and Medical Research Council
NICHD	National Institute of Child Health and Human Development
NK	natural killer
NO	nitric oxide
NOx	nitrogen oxides
8-NO_2Gua	8-nitrosoguanine
NOAEL	no observed adverse effect level
NPDES	National Pollutant Discharge Elimination System
NTCP	Na+/taurocholate cotransporting polypeptide
NTP	National Toxicology Program

OAT	organic acid transporter
OATP	organic anion transporting polypeptide
OCC	Odense Child Cohort
OCM	organotypic culture model
8-OHdG	8-hydroxy-2′-deoxyguanosine
OR	odds ratio
8-oxodG	8-oxo-2′-deoxyguanosine
PAH	polycyclic aromatic hydrocarbon
PanIN	pancreatic intraepithelial neoplasia
PBDE	polybrominated diphenyl ether
PBMC	peripheral blood mononuclear cells
PBPK	physiologically based pharmacokinetic
PCB	polychlorinated biphenyl
PCDD	2,3,7,8-substituted polychlorinated dibenzodioxin
PCDF	2,3,7,8-substituted polychlorinated dibenzofuran
PCNA	proliferating cell nuclear antigen
PCO	palmitoyl coenzyme A oxidase
PCR	polymerase chain reaction
PFAA	perfluoroalkyl acid
PFAS	perfluoroalkyl and polyfluoroalkyl substances
PFHpS	perfluoroheptane sulfonate
PFHxS	perfluorohexanesulfonic acid
PFNA	perfluorononanoic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
PGF	prostaglandin
PHA	phytohaemagglutinin
PKA	protein kinase A
PKC	protein kinase C
PLCO	Prostate, Lung, Colorectal, and Ovarian Cancer Screening Trial
PM	particulate matter
$PM_{2.5}$	particulate matter with diameter < 2.5 μm
POP	persistent organic pollutant
POSF	perfluorooctane sulfonyl fluoride
PPAR	peroxisome proliferator-activated receptor
ppb	parts per billion
PPE	personal protective equipment
ppm	parts per million
PR	progesterone receptor
PTFE	polytetrafluoroethylene
PUF	polyurethane foam
PWS	public water systems
PXR	pregnane X receptor
qPCR	quantitative polymerase chain reaction
QuEChERS	quick, easy, cheap, effective, rugged, safe
RACK-1	receptor for activated C kinase 1
RBC	red blood cell
RCC	renal cell carcinoma
RD	human embryonal rhabdomyosarcoma cell line
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals

RL	reporting limit
RNA	ribonucleic acid
tRNA	transfer RNA
RNS	reactive nitrogen species
ROS	reactive oxygen species
RONS	reactive oxygen and nitrogen species
RPE	retinal pigment epithelial
RR	rate ratio
RT-PCR	reverse transcription-polymerase chain reaction
RSV	respiratory syncytial virus
SCAP	sterol regulatory element-binding protein cleavage-activating protein
SD	standard deviation
SEER	Surveillance, Epidemiology, and End Results
SEM	systemic evidence map
SHBG	sex hormone-binding globulin
SIR	standardized incidence ratio
SMBCS	Sheyang Mini Birth Cohort Study
SMR	standardized mortality ratio
SNUR	Significant New Use Rules
SOD	superoxide dismutase
SPE	solid-phase extraction
SRBC	sheep red blood cell
StAR	steroidogenic acute regulatory
STEL	short-term exposure limit
$T_{1/2}$	half-life
TAC	total antioxidant capacity
TAD	total administered dose
TBARS	thiobarbituric acid-reactive substance
TCA	tricarboxylic acid
TCDD	2,3,7,8-tetrachlorodibenzo-*p*-dioxin
TCR	T-cell receptor
TDAR	T-cell-dependent antibody response
TDI	tolerable daily intake
TFE	tetrafluoroethylene
TGCT	testicular germ cell tumour
TH	thyroid hormone
TK	toxicokinetic
TL	telomere length
TNF-α	tumour necrosis factor alpha
TNP	trinitrophenyl
TPOAb	thyroid peroxidase antibody
TR	thyroid hormone receptor
TRI	Toxics Release Inventory
TSH	thyroid-stimulating hormone
TSCA	Toxic Substances Control Act
TT3	total triiodothyronine
TT4	total thyroxine
TTR	transthyretin
TWA	time-weighted average
TWI	tolerable weekly intake

UBA	Umweltbundesamt (German Environment Agency)
UCMR 3	Third Unregulated Contaminant Monitoring Rule
UK	United Kingdom
UNEP	United Nations Environment Programme
UPR	unfolded protein response
US	United States
USA	United States of America
US EPA	United States Environmental Protection Agency
US FDA	United States Food and Drug Administration
V_d	volume of distribution
vP	very persistent
WBC	white blood cell
WT	wildtype